ULTRASONIC CHARACTERIZATION OF DIFFUSION BONDS

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INTRODUCTION

The characterization of weak (low ultimate tensile stress) diffusion bonds is a generic problem which continues to challenge the QNDE community.[1] Here we present preliminary results for an approach based on ultrasound reflection from, and transmission through, a planar diffusion bond. The samples consisted of two bonded stainless steel cylinders, each 12.7 mm in diameter and 63.5 mm in length. The bonds were made by means of thin Ag layers deposited on each of the matching ends of the cylinders. Here the ultrasonic transducers are placed at the ends of the cylinders. For this geometry, some of the ultrasonic energy impinges on the walls of the cylinders and undergoes mode conversion, leading to a complex train of pulses. The appropriate formulae were obtained to identify the various signals in the pulse train and to associate their amplitudes and arrival times with their ray path histories. The technique used is based on a pulse-echo method in which the reflection and transmission coefficients of the bond are combined in such a way that the transducer transfer functions, including coupling variations, are eliminated. Two types of measurements were made on each sample: ultrasonic measurements at 15 MHz and tensile tests to ultimate failure. The samples were bonded under controlled conditions in which bonding time, temperature, and pressure were varied. The ultrasonic measurements suggest that the effective reflection coefficient of the bond may be a candidate for a potential correlation with bond strength.

PROPAGATION OF PULSES IN A CYLINDRICAL ROD

The propagation of pulses in a cylindrical rod is dependent upon the ratio of the diameter of the rod, d_r, to the wavelength λ of the waves propagating in the rod. The values of the ratio, d_r/λ, determine two wave progation regimes:

- $d_r/\lambda < 1$: guided waves propagation,
- $d_r/\lambda > 1$: wave into an infinite, nondispersive medium.

In this investigation, the diameter of the rod is 12.7 mm and the length is 127 mm. For a value of the wavelength, λ, of 0.4 mm. (corresponding to 15 MHz), the corresponding ratio of $d_r/\lambda \approx 31$. Thus, we can assume that the sound can be considered as propagating into an infinite medium.

The second important parameter which affects the propagation is the product of the transducer diameter, a, and wave number $K = 2\pi/\lambda$. For the transducer selected, which has a diameter of 6.35 mm and a central frequency of 15 MHz, $Ka \approx 100$. For this intermediate value of Ka, the transducer has a radiation pattern such that some of the energy impinges on the walls of the cylinder. Transmission of elastic pulses in metal rods has been treated in the past by a number of authors.[2,3] A typical signal tranmsmitter is shown in Fig. 1.

Several wave packets are evident in Fig. 1. Most authors agree that the wave packets arriving after the first one are most likely the result of mode conversion at the walls of the rod leading to propagation of some of the energy at shear velocities. However, there is disagreement about the details of the origin of the energy. Some researchers think in terms of the presence of edge waves emanating from the transducer edge or rim, leading to the production of shear waves in the vicinity of the transducer. Other researchers conclude that the transducer generates a group of plane waves traveling very nearly parallel to the free cylindrical wall of the rod. To satisfy the free boundary condition, such waves cannot travel alone, but must be accompanied by shear waves. We adopt the treatment of Hughes et al[3] who predict arrival times, T_a, for the wave packets according to the following expression:

$$T_a(m,n) = m(L/C_L + nD\{(C_L{}^2 - C_S{}^2)^{1/2}/C_L\, C_S\}, \qquad (1)$$

where L and D are the length and diameter of the rod, respectively; C_L and C_S are the longitudinal and shear wave velocities in the rod material, respectively. The first term on the right, marked by the integer, m, represents the wave packets traveling entirely as longitudinal waves through the length of the rod. Thus, (m = 1, N = 0) corresponds to a one-

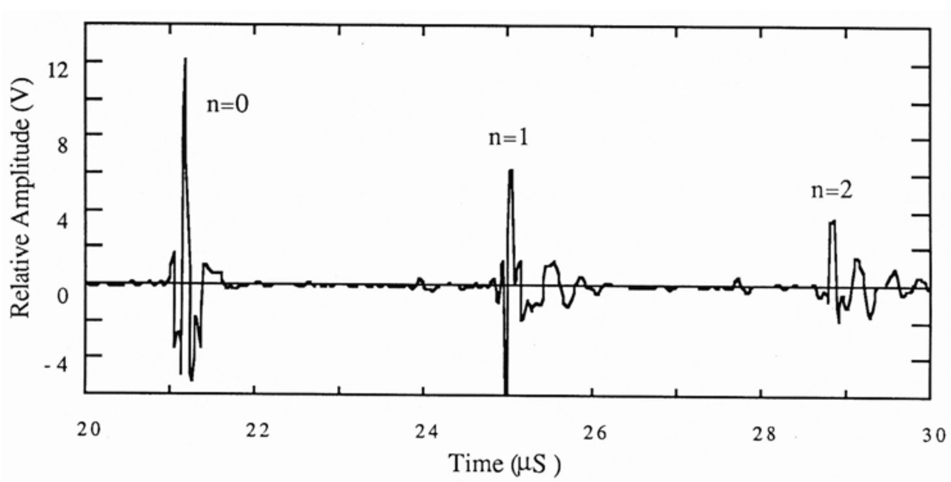

Fig.1. Waveform after progation in a rod.

way pass from transmitter to receiver at a longitudinal velocity. Higher orders of the integer, m, correspond to multiple passes with m = odd indicating arrivals at the receiver end of the rod. Between wave packets (1,0) and (3,0), there is a series of other wave packets corresponding to delays caused by a single (n = 1) or multiple (n > 1) paths in which the wave packet has crossed the narrow dimension of the rod as a shear wave at an angle assumed to be $\sin\theta\ C_S/C_L$. Figure 1 shows the wave packets corresponding to (1,0), (1,1), and (1,2). The observed arrival times of the wave packets are in reasonable agreement with those predicted by expression (1). This model gives reasonable answers for a simple piston transducer, such as a quartz plate. In the case of commercial transducers, the assumption of plane waves breaks down, the rays of energy emanating from the transducer are not parallel, and the arriving wave packet is really a collection of signals which become more and more separated as the distances traversed increase. This is thought to account for the spreading seen for the higher order packets.

MEASUREMENT METHOD

A broadband transducer was brought in contact with one side of the sample to transmit and receive short pulses. The pulse reflected from the bond is labeled R. The pulse transmitted through the bond is labeled T. The pulse totally reflected by the free surface at the opposite end of the rod, transmitted again through the bond and arriving at the transducer again is labeled TT (Fig. 2).

The effects of the bond between the transducer and the rod can be eliminated by using only the amplitude ratio R/TT in the analysis. Furthermore, access to one side of the sample is required. The two waveforms R and TT were digitized at the sampling rate of 100 MHz and stored in a computer. A temporal window (2.56 μs) was used to isolate a mode (1,0 or 1,1) in each waveforms. Although the central frequency of the transducer was 15 MHz, the amplitude maximum in the Fourier spectrum of a mode was around 6 MHz. We decided to filter the spectrum by a Hamming window centered at 6 MHz.

We define a reflexion parameter:

$$G = R/TT = \frac{\text{Amplitude of the mode (1,0) coming from the bond}}{\text{Amplitude of the mode (1,0) transmitted twice through the bond}}$$

where (1,0) designates the longitudinal signal as defined previously.

The value of the reflection coefficient, R, of the bond can be found by using the expression for energy conservation through the bond, i.e., $R^2 + T^2 = 1$, and introducing a correction for the attenuation and the mode conversion losses due to the longer path followed by the pulse TT compared to the path followed by for the pulse R. In this preliminary investigation, we study only the correlation between the values of G with the ultimate tensile stress (UTS) of the samples.

SAMPLE DESCRIPTION

Each sample consisted of two bonded stainless steel cylinders 12.7 mm in diameter and 63.5 mm in length. The bonds were made by means of thin Ag layers deposited on each of the matching ends of the cylinders by Hot Hollow-Cathode depositions. We will distinguish the two sets of samples from the kind of steel used: Vascomax and Martensitic samples. Table 1 summarizes the fabrication conditions of these samples.

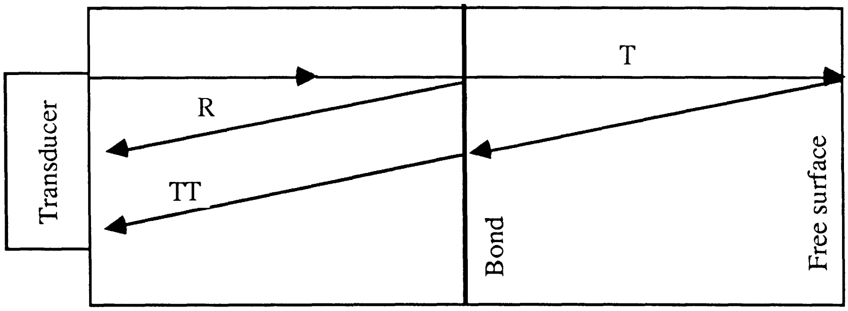

Fig. 2. Pulses R and TT used for bond characterization.

Table 1. Fabrication Conditions of the Two Sets of Samples

Specimen	Number of Samples	Bonding Temperature	Bonding Force (lbs)	Bonding Time (min)
Vascomas				
J56, J78	2	400°C	5800	10
J13, J24	2	170°C	5800	10
Martensitic				
HP-94-20 HA Series	7	700°C	4200-4800	3-5
HP-94-20 HB Series	3	700°C	300-500	3-5
HP-94-20 HC Series	7	200°C	5000	10

In terms of the metallurgical properties of the samples, Vascomax is not very different from Martensite and is characterized by large grains at high temperature that transform into lath-like structures forming oriented clusters about 50-100 μm in size which in turn are randomly oriented in the material.

RESULTS

Table 2 and 3 summarize the results for the Vascomax and Martensite samples:

Table 2. Values of G and UTS for the Vascomax Samples

Sample	G	UTS
J56	0.080	
J78	0.098	
Average:	0.089	26 ksi
J13	0.370	
J24	0.320	
Average:	0.350	2-3 ksi

Table 3. Values of G for the Martensitic Samples (HP-94-20) for the Three Different Fabrication Conditions

Sample	G	UTS
HA13	0.041	
HA70	0.036	
HA204	0.051	
HA208	0.042	
HA209	0.045	
HA217	0.042	
HA218	0.034	
Average:	0.042	50 ksi
HB11	0.033	
HB81	0.040	
HB96	0.037	Broken in handling
Average:	0.037	5 ksi
HC21	0.053	
HC27	0.075	
HC30	0.078	
HC85	0.065	
HC207	0.061	
HC220	0.058	
Average:	0.065	25 ksi

DISCUSSION AND CONCLUSION

In Fig. 3, the average values of the two ultrasonic parameters G are plotted as a function of the UTS. With one exception, the values for the average G become smaller as higher values of UTS are achieved. A curve drawn through these points is monotonic, but there are insufficient data points to develop a quantitative relationship between G and UTS. These results are consistent with the conclusions drawn previously by Thomas and Spingarn.[1] On the basis of microstructural analysis of the fracture surfaces, the authors have concluded that the weak bonds are characterized by a random distribution of small areas, typically 1-3 μm in diameter, where bonding did not take place. These areas may act to sound waves as a planar array of microcracks giving rise to reflected energy, as described by, for example, Angel and Achenbach.[4]

The point identified as anomalous martensite stands out as an exception to the main trend. Microscopic examination of the fracture surface revealed that the cause of fracture may have been related to the surface preparation rather than the fabrication conditions. There were strong indications that the mating surfaces were not flat and therefore not parallel during bonding. Optical microscopy revealed that near the edges of the samples, ring-shaped areas appeared to be unbonded, probably as a result of slight beveling during the polishing procedure. These features had the appearance of narrow circumferential surface cracks. It is somewhat surprising that these discontinuities did not affect the parameter G. One must surmise that most of the energy associated with the sound waves traveled preferentially through the central portions of the sample where the bonding was good. The presence of surface cracks is known to seriously weaken a tensile specimen so that it is not surprising that failure occurred at such low ultimate strength values.

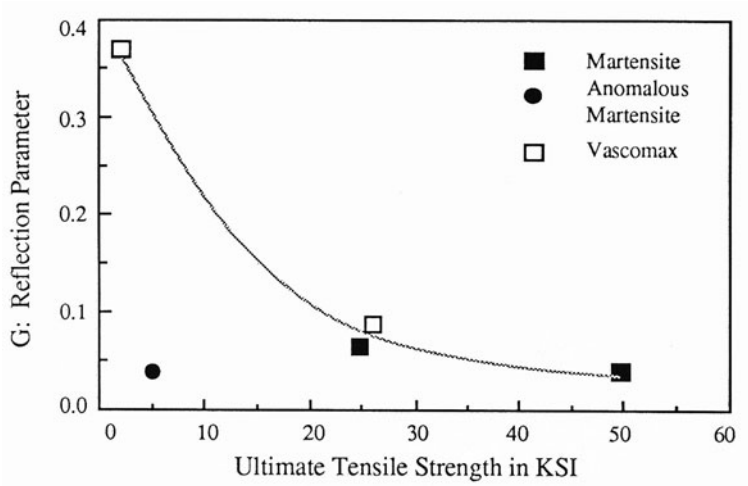

Fig. 3. Reflection parameter vs UTS.

We have presented an approach to bond inspection that divides out the transfer function of the transducer and the variability in the transducer bonding. The same method could be used to cancel the effects from temperature gradients in the specimen most likely to occur during the bonding process.

Based on the comparison between waveforms produced by a reference rod and waveforms produced by the samples, this method appears to hold promise for characterizing weak bonds in this geometry, but more data are needed before any significant conclusions can be drawn.

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